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(NASA-TM-83862) HIGH ENERGY X-RAY  
OBSERVATIONS OF CYG X-3 FOCM FOCM OSO-8:  
FURTHER EVIDENCE OF A 34.1 DAY PERIOD (NASA)  
21 p HC A02/MF A01 CSCL 03A

W82-18C65

CSCL 03A

Unclassified  
11719

G3/89

NASA

# Technical Memorandum 83862

# HIGH ENERGY X-RAY OBSERVATIONS OF CYG X-3 FROM OSO-8: FURTHER EVIDENCE OF A 34.1 DAY PERIOD?

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**NOVEMBER 1981**

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**ABSTRACT**

The X-ray source Cyg X-3 (=4U2030+40) was observed with the high energy X-ray spectrometer on OSO-8 for two weeks in 1975 and in 1976 and for one week in 1977. No change in spectral shape and intensity above 23 keV was observed from year to year. No correlation is observed between the source's intensity and the phase of the 34.1-day period discovered by Molteni et al. (1980). The pulsed fraction of the 4.8-hour light curve between 23 and 73 keV varies from week to week, however, and the magnitude of the pulsed fraction appears to be correlated with the 34.1-day phase. No immediate explanation of this behavior is apparent in terms of previously proposed models of the source.

## HIGH ENERGY X-RAY OBSERVATIONS OF CYG X-3 FROM OSO-8: FURTHER EVIDENCE OF A 34.1 DAY PERIOD?

### INTRODUCTION

Although Cygnus X-3 was one of the earliest celestial X-ray sources discovered (Giacconi et al., 1967), formulating a consistent model of its observed behavior remains an unsolved challenge in modern X-ray astronomy. The source has been detected at wavelengths ranging from gamma-ray (Gal'ner et al., 1973; Lamb et al., 1977) to radio (Gregory et al., 1972). Its flaring behavior makes it at times one of the strongest radio sources in the sky. It is at a distance of 10 kpc or more, based on 21 cm absorption lines in its radio spectrum (Lacque et al., 1972; Chu and Bieging, 1973). No optical counterpart has been identified because of the heavy obscuration over a 10 kpc path length in the direction  $\ell = 80^\circ$ ,  $b = +1^\circ$ . An infrared counterpart, stellar in appearance, has been observed at  $20^h 30^m 38^s$ ,  $+40^\circ 47' 13''$  (Becklin et al., 1972).

The 2-6 keV flux from Cyg X-3 exhibits a strong modulation with a period of 4.8 hours (Parsignault et al., 1972), and this modulation has been detected at higher X-ray (Pietsch et al., 1976), gamma ray (Lambert et al., 1977; but cf. Bennett et al., 1977) and infrared energies (Becklin et al., 1973). The 4.8-hour modulation is not detected at radio wavelengths, however (Becklin et al., 1974). The intensity modulation appears to be in phase at all wavelengths where it is detected (Mason et al., 1976; Lamb et al., 1977). Models of the source usually attribute the 4.8-hour periodicity to orbital motion of a compact star about a companion (see, for example, Basko et al., 1974).

Molteni et al. (1980) observed an intensity modulation in the 2-12 keV flux from Cyg X-3 with period  $34.1 \pm 0.1$  days. They also reported the presence of a Doppler effect in the 4.8-hour modulation "consistent with an orbital motion of period 34.1 days" and an eccentricity of  $0.6 \pm 0.3$ . In the model of the source suggested by Molteni et al., this 34.1-day period is the orbital period of the system, which modulates the X-ray flux of the system by increasing the accretion rate onto a compact secondary near periastron. The 4.8-hour period would then be interpreted as either the

rotational or precessional period of the compact secondary. Confirming the existence of this 34.1-day period is of obvious importance in determining the physical conditions existing in the source.

## OBSERVATIONS

The high energy X-ray spectrometer on board OSO-8 observed Cyg X-3 for several weeks during November and December in the years 1975, 1976 and 1977. The actual dates of observations are listed in Table 1. A complete description of the instrument and its operating environment is given by Dennis et al. (1977). The counting rate with background subtracted observed from Cyg X-3 in the 23-83 keV energy range during these observations is shown in Figure 1 as a function of the phase of the 34.1-day period calculated from the ephemeris of Molteni et al. (1980). The increase in flux by a factor of three around the time of zero phase observed by Molteni et al. between 2-12 keV in June 1977 and November 1978 is not observed by us between 23 and 83 keV.

Photon number spectra of Cyg X-3 were derived from our observations using the matrix inversion technique described by Dolan et al. (1977). A spectrum typical of those observed is illustrated in Figure 2. We observed no significant differences in the spectrum of Cyg X-3 from week to week or year to year. Because of the limitations imposed by counting-rate statistics, we must derive spectra by summing observations made over several days. The photon number spectra we observed could be acceptably represented above 23 keV either by a power law,

$$\frac{dN}{dE} = C [E/E_0]^{-\alpha} \text{ photons cm}^{-2} \text{ s}^{-1} \text{ keV}^{-1}, \quad (1)$$

or by a thermal bremsstrahlung spectrum,

$$\frac{dN}{dE} = \frac{K}{E^{1.4}} \exp \{-(E-E_0)/kT\} \text{ photons cm}^{-2} \text{ s}^{-1} \text{ keV}^{-1}, \quad (2)$$

where  $E$  is the photon energy in keV. Individual values of the parametric representations for each spectrum are listed in Table 1. The uncertainties given represent the 68 percent confidence interval

$(\chi^2_{\text{min}} + 2.3)$  calculated by the method of Lampton et al. (1976), and may be taken to represent the one standard deviation uncertainties. The normalization energy,  $E_0$ , was chosen to circularize the contours of equal  $\chi^2$  in parameter space, indicating the independence of the two parameters in that space. The spectrum of Cyg X-3 above 20 keV is consistent with that observed by Ulmer et al. (1974) in July 1972, Ulmer (1975) in February 1973, Pietsch et al. (1976) in February 1975, Meegan, Fishman and Haymes (1979) and Reppin et al. (1979) in October 1977.

The 23-73 keV flux from Cyg X-3 was analyzed for the 4.8-hour modulation by folding the data into five equally sized phase bins modulo the period given by Parsignault et al. (1976),  $p = 0.1996814d$ . Because of the extreme stability of the period over a duration of years ( $\dot{P}/P \leq 7 \times 10^{-7} \text{ yr}^{-1}$ ; Mason and Sanford, 1979), the same period was used at all epochs of observation. In the ephemeris of Parsignault et al. (1976), zero phase is the time of X-ray minimum and occurs at  $T_0 = \text{JD } 244\,0949.9176$ . The resulting light curve was analyzed for pulsation by fitting a sinusoidal function,

$$S_i = a_0 + a_1 \cos [2\pi(\phi_i - \delta)] \quad (3)$$

where  $S_i$  is the flux in counts  $\text{s}^{-1} \text{ keV}^{-1}$  in phase bin  $i$ ,  $a_0$  is the average flux during the observation,  $a_1$  is the amplitude of the sinusoidal modulation,  $\phi_i$  is the central phase of bin  $i$ , and  $\delta$  is the phase of maximum of the fitted sinusoid. The pulsed fraction is then calculated as

$$p_F = a_1/a_0 \quad (4)$$

The one standard deviation errors assigned to our estimate of  $p_F$  are calculated, using the method of Lampton et al. (1976), as those values of  $p_F$  given by the values of  $a_1$  for which  $\chi^2$  increases from that of the best sinusoidal fit by 1.00.  $a_1$  is considered the only free parameter in calculating the assigned errors.  $a_0$  is determined from the data and  $\delta$  must be within one bin width, or 0.20 in phase, of the ephemeris value for the pulsation to be accepted as reliably detected. Two standard deviation upper limits are those values of  $p_F$  for which the value of  $\chi^2$  increases from that of the best sinusoidal fit by 4.00.

As can be seen by inspection of Table II, the 4.8-hour pulsed fraction appears to vary from week to week. A  $\chi^2$  test rejects the hypothesis of a non-varying pulsed fraction at the  $2.4\sigma$  level of significance. Typical light curves obtained for times of high and low pulsed fraction are shown in Figure 3. The phase of minimum of the fitted sinusoidal light curve (Eq. (3)) agrees with that predicted by the ephemeris of Parsignault et al. (1976) in those cases for which a non-zero pulsed fraction is reliably detected. For the other three cases, not only is the pulsed fraction not significant at the  $2\sigma$  level, but the phase of minimum of the fitted sinusoid is also in disagreement with the adopted ephemeris. Because the phase of minimum of the fitted sinusoidal light curve is determined by the data, but agrees with the ephemeris phase of X-ray minimum when the 4.8-hour modulation appears present, our observations seem able to detect the 4.8-hour modulation at levels of pulsed fraction previously detected by others at lower energies. The light curve of Figure 3(a), obtained when the 4.8-hour modulation was detected, is also typical of Cyg X-3, with a single pulse per period having a quasi-sinusoidal shape with a steeper decline than rise. We interpret these results as indicating that the 4.8-hour modulation of the 23-73 keV flux of Cyg X-3 has a pulsed fraction which varies on a time scale of tens of days.

The magnitude of the pulsed fraction we observe shows no correlation with intensity in either the 23-73 keV or 23-33 keV band. All of our positive detections of 4.8-hour pulsed flux between 23 and 73 keV, however, occur between 34.1-day phases 0.3 and 0.8, while no pulsed flux is detected between 34.1-day phases 0.9 and 0.2. This behavior is exhibited by the source in observations taken during three separate years. If the high energy pulsed flux from Cyg X-3 continually behaves in this manner, it is further evidence that the 34.1-day period is real.

There are three other published measurements of the pulsed fraction of Cyg X-3 above 20 keV of which we are aware. Pietsch et al. (1976) measured the 32-64 keV pulsed fraction with a balloon-borne detector. The observation occurred at 34.1-day phase 0.21, in the transition zone of our observational coverage between the phases for which we do not see a pulsed flux, and those for which we do. Pietsch et al. found  $P_F = 0.37$  ( $+0.31, -0.29$ ), where the quoted errors are derived

from a  $(\chi^2_{\text{min}} + 1)$  calculation. Ulmer et al. (1974), using OSO-7, observed the 4.8-hour modulation between 21 and 98 keV over 34.1-day phases 0.90 to 0.05. They quote a pulsed fraction consistent with zero, with an upper limit corresponding to  $P_F \leq 0.4$ . Interestingly, the 6-21 keV flux observed simultaneously did exhibit a detectable pulsed fraction  $P_F = 0.52 \pm 0.16$ . Ulmer et al. note that "the pulse became undetectable just above 20 keV." Ulmer (1975) analyzed OSO-7 data obtained between 34.1-day phases 0.43 and 0.50 and derived  $P_F \leq 0.65$  between 22 and 100 keV. The 7-22 keV flux observed simultaneously had  $P_F = 0.36 \pm 0.16$ . All of these observations thus appear consistent with the correlation which we observe between the pulsed fraction and the 34.1-day phase, although they provide no independent evidence for the pulsed fraction dropping to unobservable values around 34.1-day phase zero.

From the measurements of  $P_F$  reported by Leach et al. (1975) at lower energies, the 2-10 keV pulsed flux exhibits no such correlation with 34.1-day phase. The 4.8 hour modulation is always present in the 2-10 keV flux between 34.1-day phases 0.80 and 0.20; Leach et al. report values of  $P_F$  during this phase interval which range between  $(0.28 \pm 0.02)$  and  $(0.47 \pm 0.03)$ .

## DISCUSSION

No immediate explanation of the observed variation of the pulsed fraction of the 23-73 keV flux with 34.1-day phase is apparent in terms of previously proposed models of Cyg X-3. If the 34.1-day period is the orbital period of a binary (Molteni et al., 1980), then the 4.8-hour period may be the rotational period of a compact secondary near which the X-rays are generated (Syunyaev, 1976) or the precession period of a rapidly rotating neutron star secondary, as in the model, e.g., of Treves (1973). Neither possibility offers a simple method of maintaining the 4.8-hour modulation observed at lower X-ray energies at all phases of the 34.1-day binary period while simultaneously suppressing it near periastron at higher X-ray energies. If, conversely, we identify the 4.8-hour modulation as the orbital period of a binary system (Pringle, 1974; Davidsen and Ostriker, 1974; Milgrom, 1976; Fabian et al., 1972), the 34.1-day period can then be ascribed to the apsidal motion of the binary orbit (Milgrom and Pines, 1978). Quite apart from the difficulties this scheme has in

explaining the 34 day intensity modulation observed at lower energies, these attributions have no better success at explaining the different behavior of the pulsed fraction at high and low X-ray energies. White and Holt (1981) attribute the 4.8-hour sinusoidal light curve observed from Cyg X-3 to the partial occultation of an accretion disk corona by a bulge at the edge of the accretion disk caused by material inflowing from a binary companion in an orbit of period 4.8 hours. The variation in pulsed fraction could then be ascribed in this model to the precession with a 34-day period of the accretion disk, which would have to be tilted to the orbital plane of the binary. This model would once again predict a simultaneous variation of pulsed fraction at all energies. Models which attribute the 4.8-hour modulation to variations in mass accretion rate caused by the physical pulsation of one of the stars in the binary system (Bruhweiler, 1973), although not as developed as many of the other models, seem equally unable to explain this phenomenon.

It is still possible, of course, that the variations in pulsed fraction we observed above 20 keV over three separate years have some entirely different mechanism as their cause, and that the correlation with the 34.1-day ephemeris of Molteni et al. is purely coincidental. In view of the importance of the effect, if real, in defining models of the source, further observations of the pulsed fraction of Cyg X-3 above 20 keV as a function of 34.1-day phase are required to confirm or deny the reality of the correlation we observe.

TABLE I  
Spectral Parameters, Cyg X-3

Date of Observation	E(keV)	Power Law Representation <sup>a</sup>			Thermal Bremsstrahlung Representation <sup>b</sup>	
		$C \times 10^4$	$\alpha$	$E_0$ (keV)	$K \times 10^2$	$kT$ (keV)
1975 Nov. 11-15	26-114	3.56 $\pm$ 1.73	2.84 (+1.22, -0.95)	40.5	4.74 $\pm$ 1.31	27 (+26, -23)
Nov. 15-17	26-114	8.01 $\pm$ 2.66	2.88 (+1.00, -0.83)	40.1	5.92 $\pm$ 1.38	15 (+14, -12)
Nov. 24-30	26-114	2.89 $\pm$ 1.59	2.29 (+1.05, -0.93)	46.3	5.69 $\pm$ 2.00	51 (+69, -49)
Nov. 30-Dec. 4	26-114	9.00 $\pm$ 3.57	3.45 (+1.83, -1.20)	35.5	4.50 $\pm$ 1.24	14 (+16, -13)
1976 Nov. 8-16	26-114	7.95 $\pm$ 3.65	3.41 (+2.19, -1.20)	35.2	5.81 $\pm$ 1.59	20 (+20, -18)
1977 Nov. 11-17	18-108	9.61 $\pm$ 3.31	2.32 (+1.03, -0.85)	23.7	8.26 $\pm$ 3.65	32 (+39, -27)

a. Equation (1) in text.

b.  $E_0 = 25$  keV for all thermal bremsstrahlung representations; Equation (2) in text.

TABLE II  
Pulsed Fraction, 4.8-hour Modulation, 23-73 keV

Date	34.1 Day Phase <sup>a</sup>	p <sub>F</sub> <sup>b</sup>	Phase of Minimum <sup>c</sup>
1975 Nov. 11-17	0.94-0.14	≤ 0.39	0.55
	0.34-0.41	0.55 (+0.18, -0.10)	0.95
	0.41-0.57	0.39 (+0.10, -0.16)	0.15
	0.57-0.63	≤ 0.63	0.34
1976 Nov. 8-13	0.59-0.72	0.46 (+0.10, -0.16)	0.82
	0.02-0.25	≤ 0.25	0.69
1977 Nov. 11-17	0.37-0.57	0.41 (+0.37, -0.41)	0.85

a. Based on P = 34.1 d, To = JD 244 3309.5 (Molteni et al., 1980)

b. 2  $\sigma$  upper limits

c. Based on the ephemeris of Parsignault et al. (1976).

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## FIGURE CAPTIONS

**Fig. 1** The 23-83 keV counting rate, with background subtracted, observed from Cyg X-3 during the times of observation in Table I. The counting rates are plotted as a function of 34.1-day phase given by the ephemeris of Molteni et al. (1980). Error bars represent  $\pm$  one standard deviation uncertainties derived from the statistics alone.

**Fig. 2** The photon-number spectrum of Cyg X-3 observed 1975 November 15-17. Parametric representations are given in Table II. The error bars represent  $\pm$  one standard deviation uncertainties derived from the statistics alone.

**Fig. 3** (A) The 23-73 keV light curve of Cyg X-3 observed 1975 November 25-27 (cf. Table II) as a function of 4.8-hour phase given by the ephemeris of Parsons et al. (1976). The same data are repeated twice for clarity. All phase bins have  $\pm$  one standard deviation uncertainties derived from the statistics alone similar to the error bar shown.  
(B) The same as (A), except for 1975 November 11-12.







